THE WEATHER AND CIRCULATION OF MAY 1959

INCLUDING AN ANALYSIS OF PRECIPITATION IN RELATION TO VERTICAL MOTION

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1. INTRODUCTION

The May pattern at the 700-mb. level over the United States was one of large amplitude with a trough in the West and ridge in the East. Except for a short break, this system persisted throughout the month, bringing repeated outbreaks of cold maritime air into the western states and unusual warmth in the East. The well-marked mean frontal boundary thus established gave rise to frequent storminess and abundant rainfall over much of the country.

2. MEAN CIRCULATION AT 700-MB.

Perhaps the most striking aspect of the 700-mb. mean map for the month (fig. 1) was a tendency toward blocking activity. One blocking High was centered over northeastern Siberia and another northeast of the Caspian Sea. In addition, large amplitude ridges with sizeable positive height anomaly centers were located over Alaska and Britain. Since both these features were roughly out of phase with the lower latitude circulation, the pattern which developed was strongly difluent over the western coast of North America and Europe and confluent downstream over eastern North America and Eurasia. The Pacific westerlies to the south of the block were relatively flat with a tendency toward a weak trough off Japan and another in the central Pacific. This latter feature, though weak in the mean and variable during the month, was in a position to support the trough in the western United States and its disappearance about mid-month led to the only major (though transitory) change from the dominant weather pattern for the month.

The pattern depicted in figure 1 differed in several significant aspects from that of April [1]. The change chart (fig. 2) indicates a marked increase in blocking activity with large rise centers over northern Asia and the eastern Atlantic. Also, the deepening in the western United States together with the ridging in the East were sufficient to reverse the circulation regime over the country.

Since blocking played a major role during the period, its effect was studied by preparing harmonic analyses for the meridional component of the 700-mb. flow around each latitude circle. The graphs of amplitude versus wave number at 60° N. and 40° N. were computed following the procedure described in [4] and are displayed as figure 3. In a characteristic blocking situation with large features at high latitudes one would expect amplitudes in the low wave numbers to be dominant. On the other hand, the relatively short wave lengths at lower latitudes would be expected to favor higher wave numbers. To a degree this is substantiated by the data of figure 3. At 60° N., for example, the amplitude of the 2nd harmonic exceeds that calculated from the normal map [8], while all others, except wave 5, are less than normal.

At 40° N. on the other hand, the amplitude of harmonics 5, 6, and 7 were clearly greater than normal, though 1, 2, and 3 still retained values about average in magnitude. The curves at 40° N. display the double maximum described by several authors as characteristic (c.f., [9], [10]) with a primary maximum in the longer wave lengths and a secondary maximum near wave 6 or 7. This distribution is also discernible in the curve representing the normal but with greatly diminished amplitude in the higher wave numbers. The tendency for the shorter wave lengths to predominate is further illustrated by comparing the percentage of the total variation in the pattern [4] accounted for by wave 5, 6, and 7 in May 1959 (26 percent) with the corresponding percentage for the normal (4 percent). Thus the waves within this band were unusually energetic this month, and even wave 7 was sufficiently strong and persistent to account for a surprising 12 percent of the total variation in the pattern.

The zonal index underwent a double oscillation during the month (fig. 4). The first was minor in nature, but the second was more pronounced and amounted to a major index cycle for this season of the year. It began when the zonal index briefly reached 10 m.p.s. for the 5-day period ending May 11, dropped to a low value of 4.4 m.p.s. for the period ending the 27th, and then recovered rapidly, again exceeding 10 m.p.s. by June 6.

3. MEAN TEMPERATURE IN THE UNITED STATES

The change in circulation over the United States from April to May brought about a corresponding reversal in the temperature pattern. The observed temperature distribution in May (fig. 5) was one of sharp contrasts with

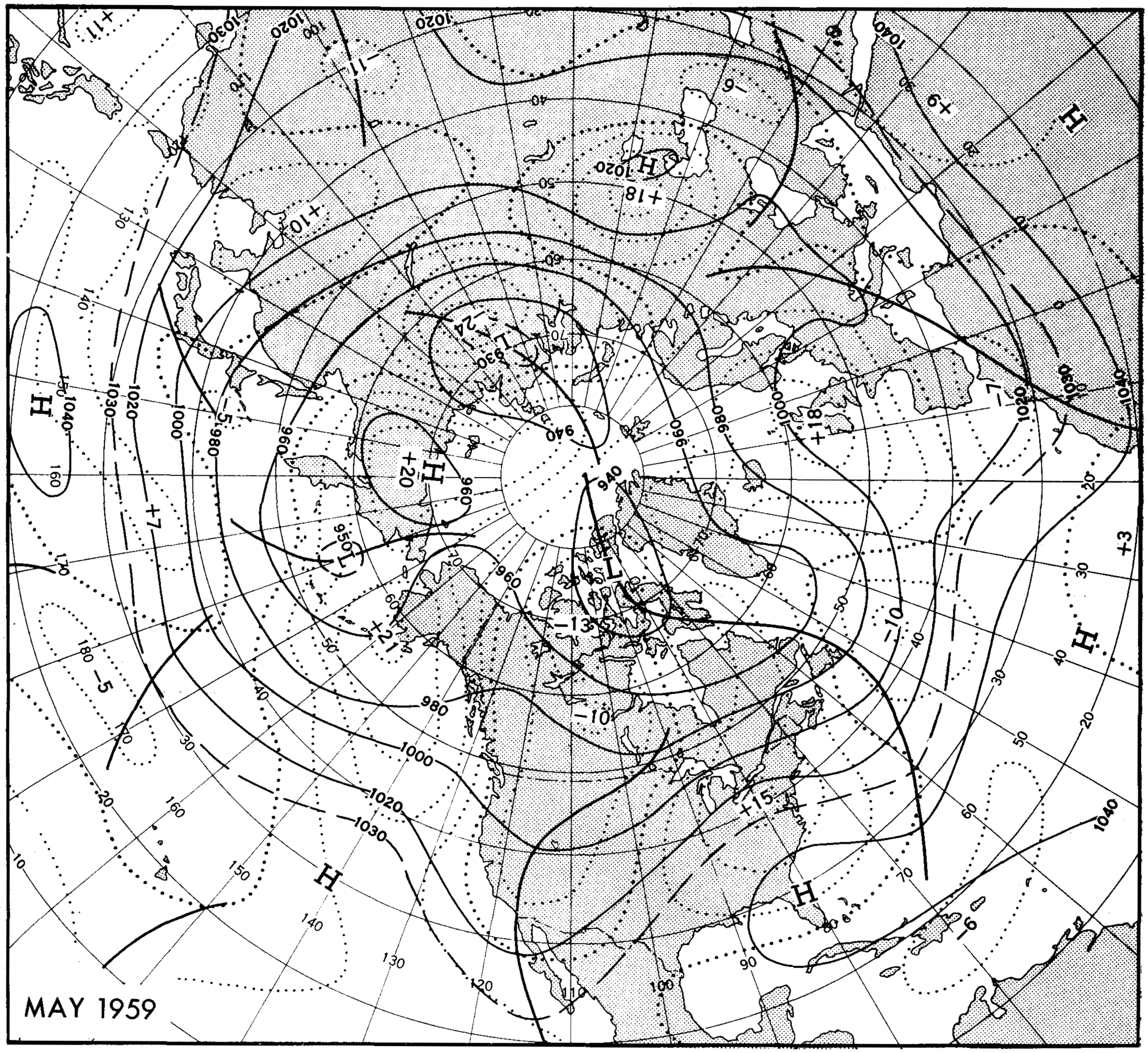


FIGURE 1.—Mean 700-mb. height contours (solid) and departures from normal (dotted) (both in tens of feet) for May 1959. Over the United States the pattern of trough in the West and ridge in the East represented a reversal from the preceding month. Blocking was active, as indicated by the extensive areas of positive anomaly over polar and subpolar regions.

cold maritime air masses predominating in the mean trough in the West and warm tropical air in the eastern ridge. In the West this resulted in a regime which was cooler in May than in April by two classes over a broad area covering most of the western Plateau (fig. 6). At Fresno, Calif., the temperature dropped 4 classes from much above normal in April to much below in May. Maximum warming, on the other hand, occurred in the eastern Texas-Louisiana area, with a finger of two-class changes extending northward to the Lakes.

At Ely, Nev., the average monthly temperature of 47.4° F. was the coldest of record for May. On the other hand, Muskegon, Mich., experienced the warmest May since records began with an average 60.5° for the month.

4. EVOLUTION OF BLOCKING

The tendency for blocking to be frequent in May has been discussed by several authors [5, 7], and this month was no exception. Two remarkable surges occurred, one of which influenced primarily the eastern sector of the

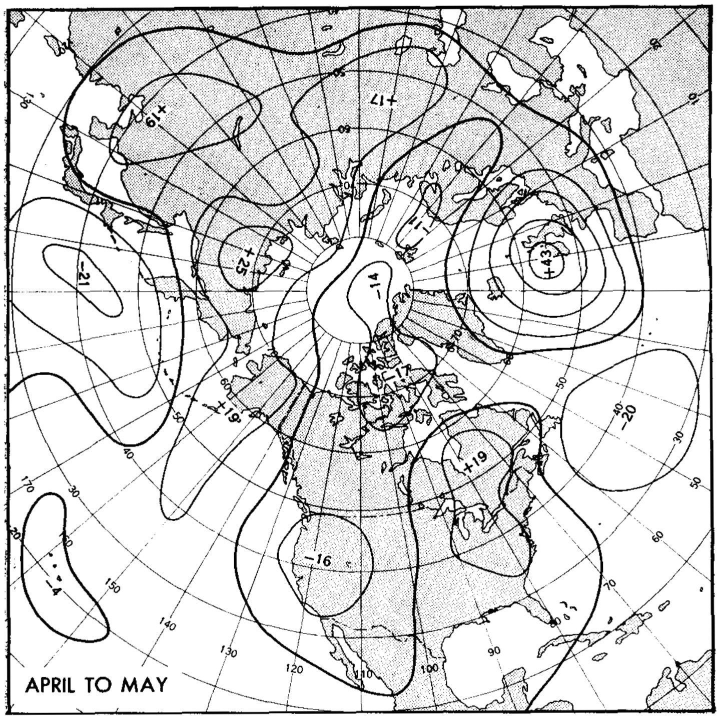


FIGURE 2.—Change of mean 700-mb. height departure from normal (tens of feet) from April to May 1959. Blocking increased over the Siberia-Alaskan region and also over the eastern Atlantic. The falls in the western and rises in the eastern United States resulted in a change of phase from the April pattern.

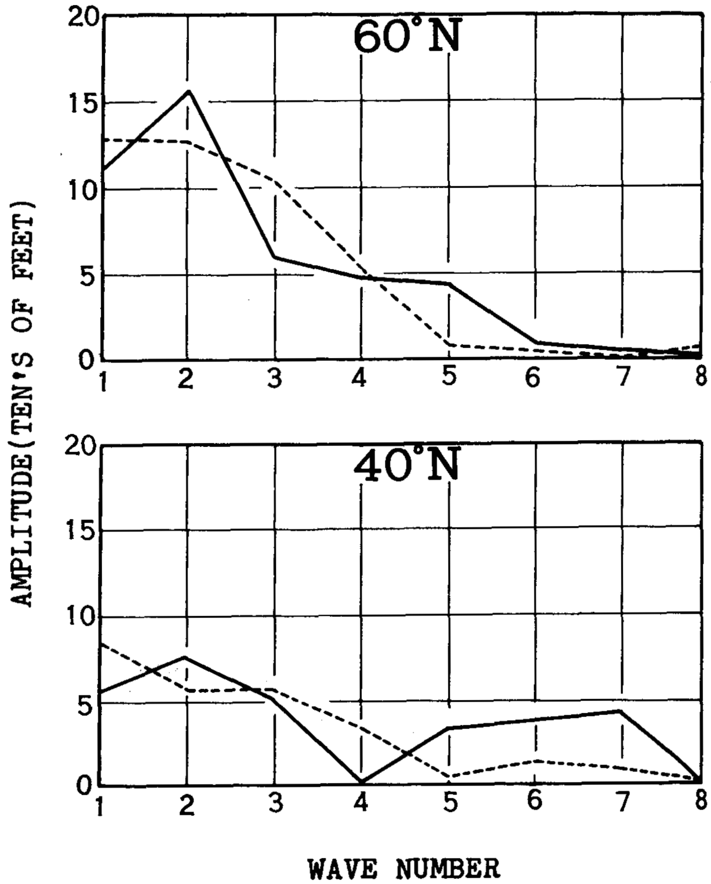


FIGURE 3.—Amplitude in tens of feet of the zonal harmonic wave components at 60° N. and 40° N. for the 700-mb. mean chart for May 1959. At 60° the maximum amplitude was in the second harmonic. At 40° N. the graph exhibits a double peak with maxima in waves 2 and 7. The fifth, sixth, and seventh harmonics were markedly above normal (dashed), illustrating the tendency for short wave lengths to be associated with blocking.

Northern Hemisphere and the other the western. To follow their evolution, the series of 5-day mean maps approximately a week apart (fig. 7) has been prepared. The history of the first blocking wave began with the subpolar High over Alaska on the first chart (fig. 7a) of this series. This center shifted rapidly to northeastern Siberia on the subsequent map (fig. 7b), and its influence can be traced even farther westward as a band of positive height anomaly extended across the Arctic basin and joined the next upstream ridge near Novaya Zemlya. Thereafter, the original center sank southward to the neighborhood of Kamchatka (fig. 7c) and then appeared to join with the subtropical ridge in the western Pacific (fig. 7d).

However, the blocking surge, as distinguished from this center, can be traced on to the west as heights subsequently rose over 600 ft. in the Scandinavian region from the second to the third chart of the series, resulting in a marked retrogression of the Russian blocking ridge to that region. The North Atlantic was next affected, and a closed anticyclone appeared just north of Britain (fig. 7d). By the end of the month, this surge seemed to come to an abrupt end as heights fell rapidly at northerly latitudes from Europe to North America.

So far this phenomenon has been treated in terms of ridges, but one could equally well direct attention to the remarkable sequence of Lows cut off or depressed to lower latitudes: first over the sea of Okhotsk (fig. 7a), then just north of Lake Baikal and over the Black Sea (fig. 7b), then near the Adriatic and Central Atlantic (fig. 7c), and finally over the Bay of Biscay and the Labrador Shelf (fig. 7d). This long list illustrates the widespread influence which such a blocking impulse can exert and highlights its possible importance as a tool in longer period forecasting. From its position over Alaska at the beginning to that north of Scotland near the end of the period it traversed approximately 205° of longitude in 19 days or about 11° of longitude per day, an unusually rapid pace.

For the western sector of the hemisphere, however, the more important blocking complex was that centered off the Labrador coast as the month opened (fig. 7a). In successive weeks this surge, spreading upstream:

1. Amplified the United States ridge and cut off the Low near Newfoundland (fig. 7b).

2. Amplified the ridge in western Canada and cut off the Low near James Bay (fig. 7c).

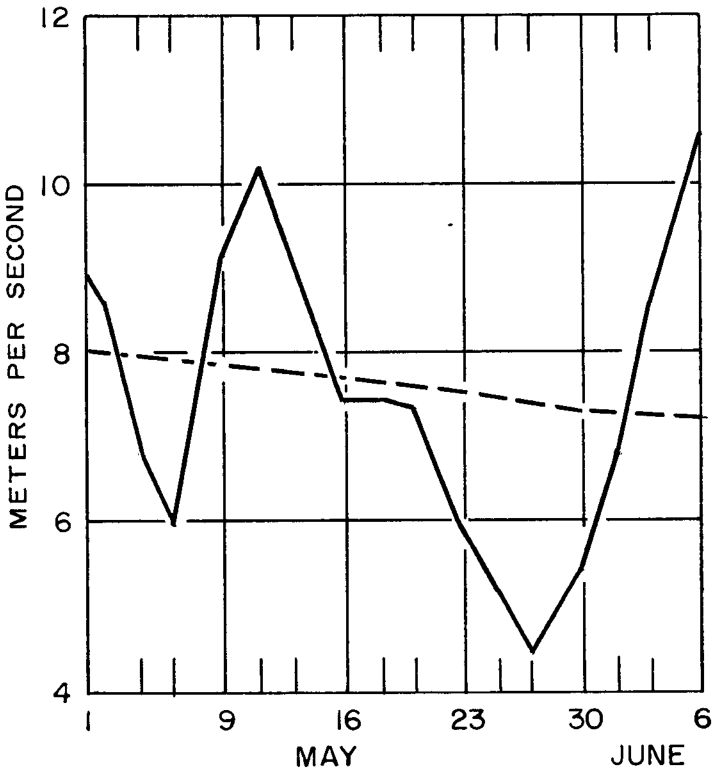


FIGURE 4.—Time variation during May and early June 1959 of the 5-day mean values of the zonal westerlies in meters per second (plotted on the last day of the period). The zonal index is computed for the western sector of the hemisphere for the latitude belt 35°—55° N. A pronounced index cycle followed an earlier minor variation, with the zonal index reaching a minimum during the last week of May.

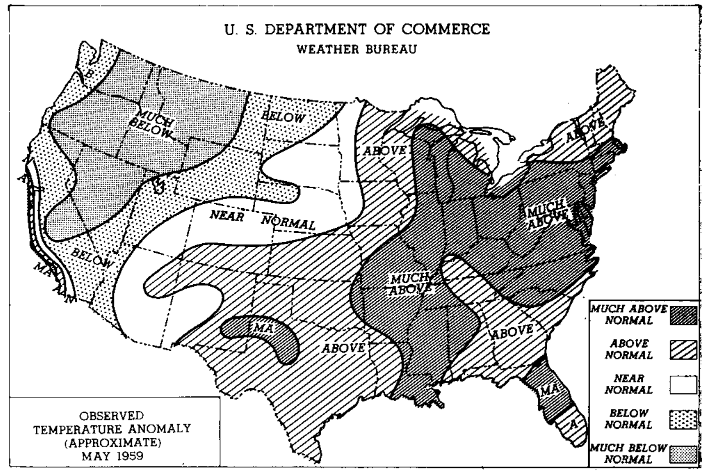


FIGURE 5.—Observed temperature anomaly for May 1959 expressed in five classes defined so that near, below, and above normal each comprises one-fourth of the monthly mean temperatures for May over the 30-year period 1921 through 1950. The remaining fourth is divided equally between the much above and much below categories. A strong east-west temperature gradient existed, with very cold conditions prevailing over the West (with the exception of coastal California) and very warm weather over roughly the eastern two-thirds of the country. A marked frontal system separated these extremes, and wave activity resulted in widespread precipitation and severe storms.

3. Amplified the eastern Pacific ridge, cut off the depression in the Southwest, and began to depress the cyclone in the eastern Aleutians (fig. 7d).

4. Amplified the pattern over northeastern Siberia and cut off the deep system in the eastern Aleutians (fig. 7e).

This singular evolution paralleled the first such system in many respects and can be described as typical of many blocking sequences. It was intimately connected with the index cycle previously described, the low point of the latter being reached as the blocking reached maximum coverage and development in the western sector of the hemisphere. Also, subsequent continued retrogression of blocking into Asia in early June allowed the zonal index to again climb to above 10 m.p.s. and complete the cycle. The average speed of retrogression of blocking in this case was about 6° of longitude per day, which is considerably slower than the first case described.

5. WEEKLY WEATHER AND CIRCULATION OVER THE UNITED STATES

The wave train over the United States was progressive for the first portion of the month. The trough initially

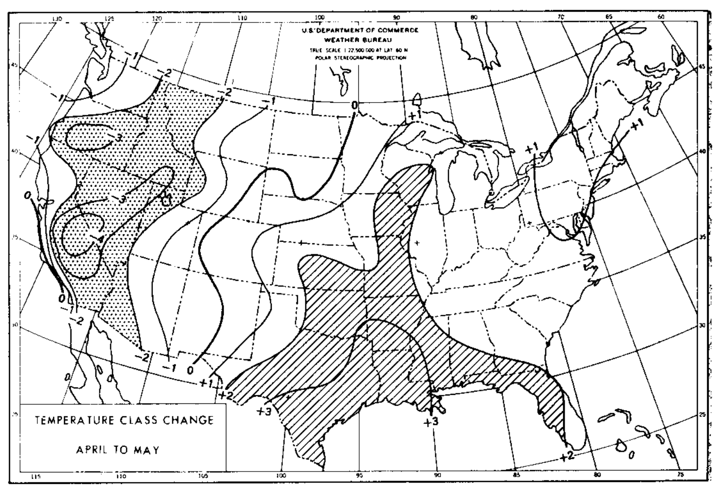
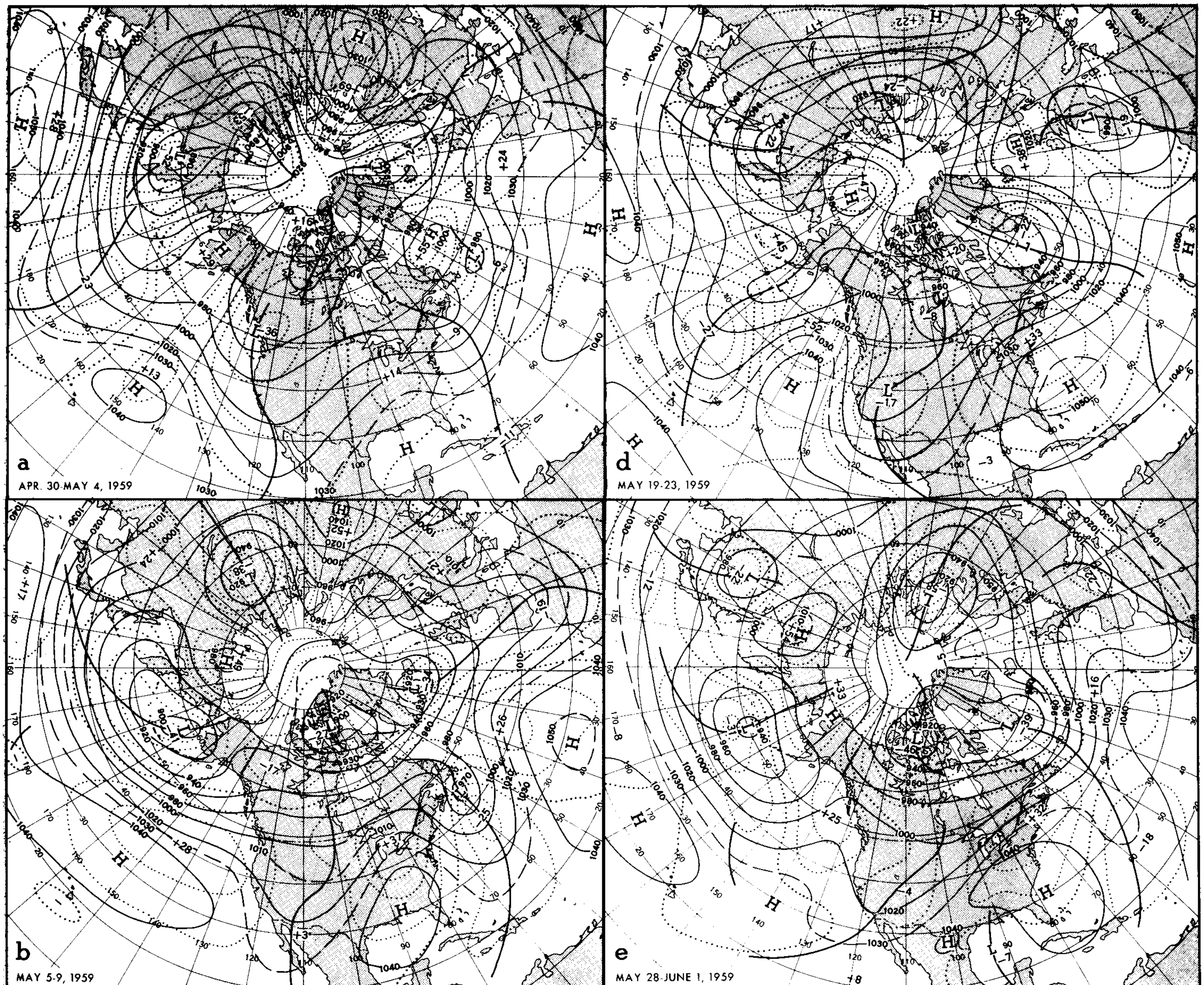


FIGURE 6.—The number of classes the anomaly of temperature changed from April to May 1959. Marked cooling took place over a broad area of the West, with warming over most of the remainder of the United States except for the northeastern States.

along the west coast (fig. 7a) marched steadily eastward and by the fourth map of the series (fig. 7d) was well out in the Atlantic. It has been mentioned that blocking served to amplify first the ridge in advance of this trough (fig. 7b) (thus advecting warm moist air into the Mississippi Valley) and subsequently the Canadian ridge in its rear (fig. 7c) (thus bringing down unusually cold air).



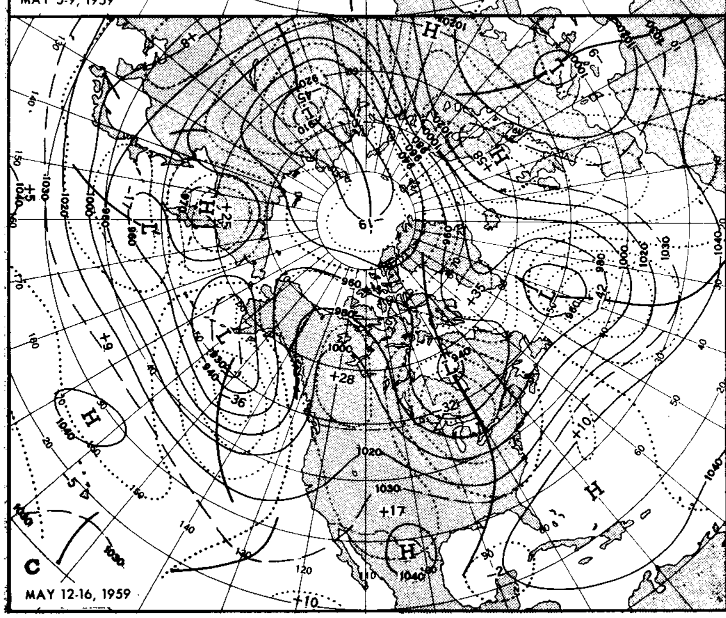
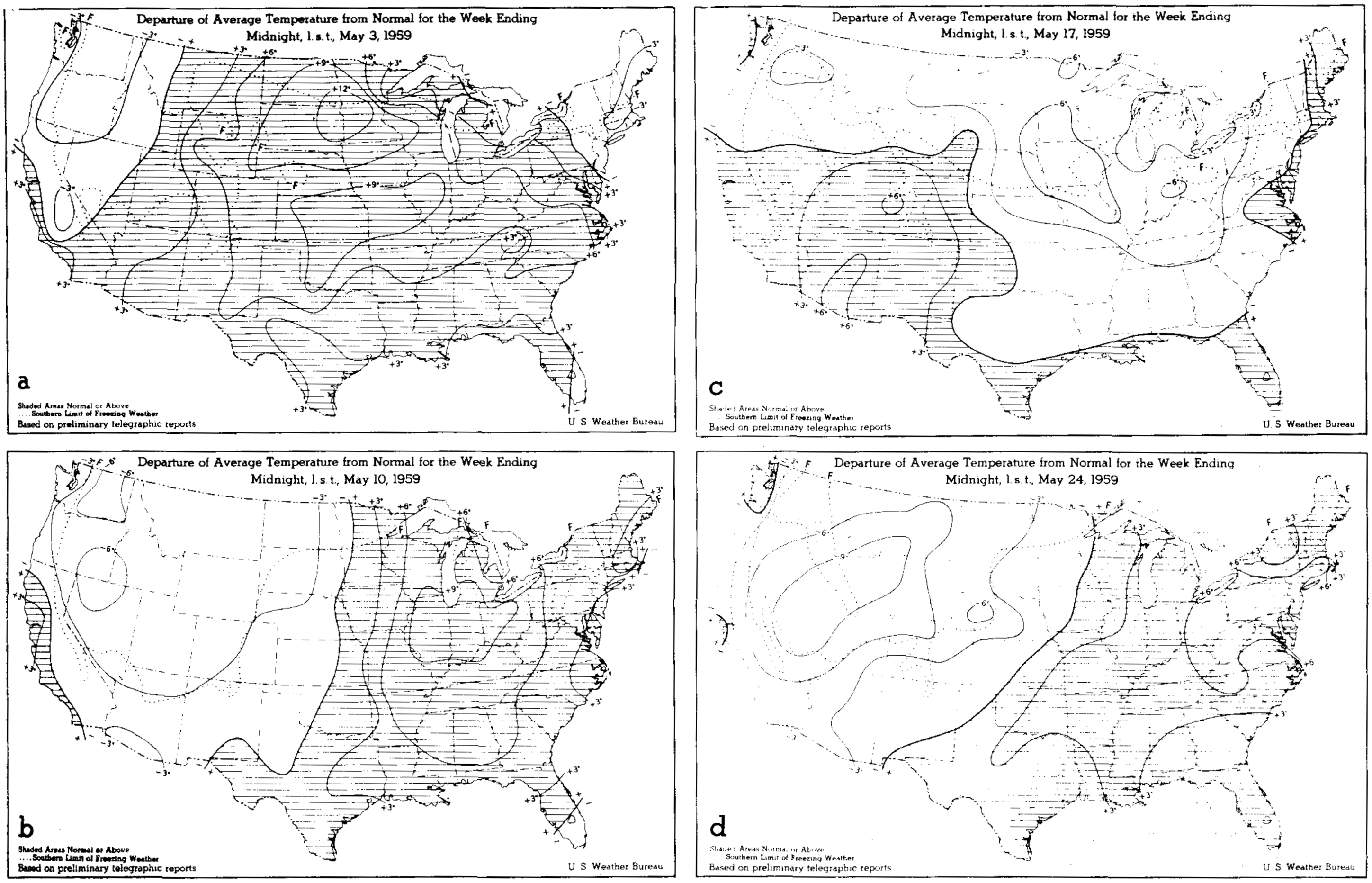


FIGURE 7.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for (a) April 30–May 4, (b) May 5–9, (c) May 12–16, (d) May 19–23, and (e) May 28–June 1, 1959. A mean trough, which entered the west coast early in the month, marched regularly across the country and passed through the East about mid-month. Thereafter it progressed rapidly into the Atlantic, and the pattern over the United States reverted to the original one with a deep trough in the West and ridge in the East. The May index cycle appears related to the blocking wave which emanated from the Atlantic toward the end of April and can be traced westward to the Pacific by late May.



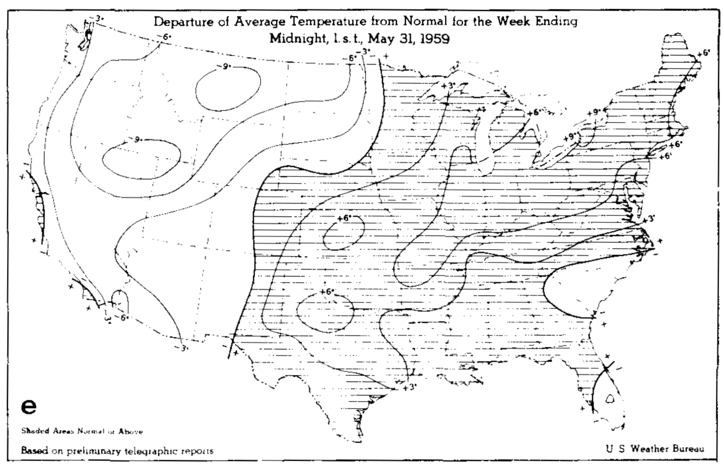


FIGURE 8.—Departure of average temperature (° F.) from normal for the weeks ending at midnight local time (a) May 3, (b) May 10, (c) May 17, (d) May 24, and (e) May 31, 1959. The cold air which entered the Pacific States early in May marched steadily eastward until it overlay most of the East by the week ending May 17. By that time, however, above normal temperatures appeared in the Southwest and subsequently overspread the East by the following week (ending May 10). Thereafter, this regime became very persistent and largely determined the character of the temperature anomaly distribution for the month. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLVI, Nos. 18 through 22, 1959.)

Along the boundary between these contrasting air masses severe frontal weather developed with thunderstorms, hail, high winds, and a number of tornadoes. As a result precipitation was heavy over much of the area between the Rockies and the Alleghenies, and was locally excessive over the Mississippi and Ohio Valleys. The eastward progress of this frontal boundary can be traced with the aid of figure 8 which shows the cold air reaching the East during the week ending May 17 (fig. 8c). This brought the only cold snap of the month to that region. Thereafter the basic circulation pattern of the month (fig. 1) became reestablished as a deep trough entered the West (fig. 7d) and the ridge over the Rockies sheared from its previous connection with the blocking ridge over northwestern Canada (fig. 7c) and amplified as it moved rapidly to the east coast (fig. 7d). It is noteworthy that the East experienced a complete reversal from very warm the second week (fig. 8b), to very cold the next (fig. 8c), and back to the original regime the fourth week (fig. 8d).

Numerous records of daily maximum and minimum temperatures were set, including maxima during the early period of 99° F. at Huron, S. Dak., on the 1st; 95° at Louisville, Ky., on the 4th; 95° at Augusta, Ga., on the 3d; and 82° at Portland, Maine, on the 11th. These were followed by record daily minima of 24° at Huron on the 15th; 38° at Wilmington, Del., on the 16th; 46° at Augusta, Ga., on the 16th; and 31° at Portland, Maine, on the 18th. The warm period which followed was not as record-breaking, though Portland, Maine, did manage to reach a new record maximum for the 28th of 88° F.

6. WEEKLY HARMONIC ANALYSIS

A harmonic analysis was also prepared for each of the charts in figure 7, and the results for 60° N. and 40° N. are presented in figure 9. As previously discussed, it was expected that blocking would tend to accentuate the longer wave lengths at high latitudes and shorter wave lengths at lower latitudes. However, the hemispheric circulation pattern is often complicated by a tendency for low zonal index in one area to be offset by high index elsewhere [2]. This suggests that perhaps fairly even distribution over a wide wave length spectrum should be more characteristic, particularly at lower latitudes. In a general way this is substantiated by the graphs at 40° N. For example, during the low index period May 19–23, the amplitudes are quite regularly distributed with an amplitude of 50 ft. in the 9th harmonic, a sizeable figure for that wave number. Apart from the relatively evenly distributed amplitudes at 40° N. over a rather wide frequency range, the maxima tended to cluster about waves 1, 2 or 3, 6 or 7, and (in the case of lowest zonal index) 8 or 9. In fact, these latter wave numbers, which correspond to wave lengths of only 45° and 40°, respectively, are quite characteristic of those regions where blocking was most active as, for example, over the western Atlantic, May 12–16 (fig. 7c); the eastern Pacific, May 19–23 (fig. 7d), and the western Pacific, May 28 to June 1 (fig. 7e). It is interesting that wave lengths of this magnitude, which are of the dimensions of daily systems, at times prevail even in the mean. It is likely that they occur mainly during periods of low index.

The effect of blocking at high latitudes, however, does seem to be to accentuate amplitudes in the low wave numbers. Wave 1 appears to be favored if only one blocking system exists or is strongly dominant. This was the case during the period April 30–May 4 when the Eurasian High was much stronger along the 60th parallel than its counterparts over Alaska and south of Greenland. However, the latter two did make substantial contributions to the amplitude of waves 2 and 3 which were also unusually large during this period.

On the other hand, when dual blocking Highs exist across the pole from each other, and this is often the case during periods of lowest index, wave 2 is principally affected. The graph at the 60° parallel for May 19–23 (fig. 9) may be cited as an example.

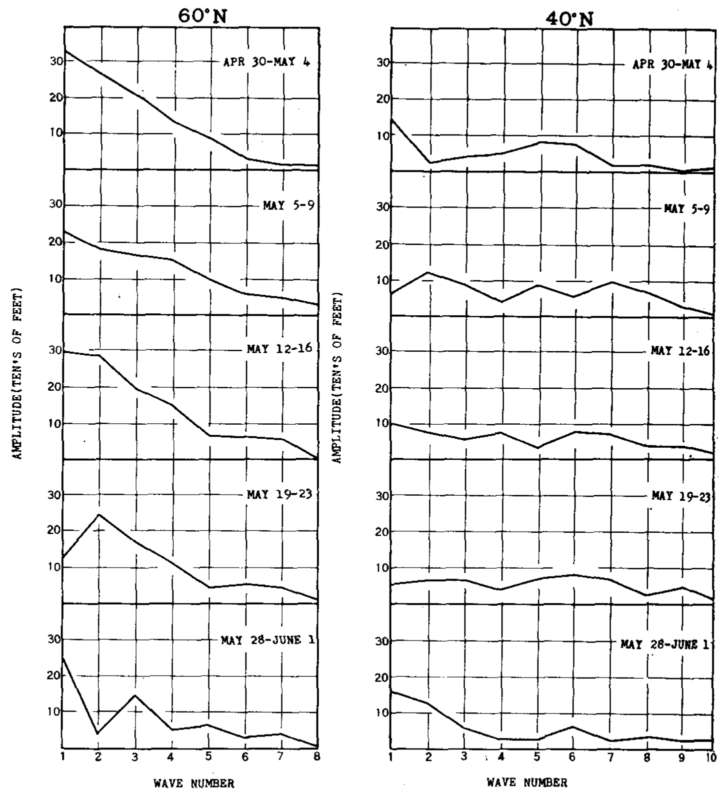


Figure 9.—Amplitude in tens of feet of the zonal harmonic wave components at 60° N. and 40° N. for 5-day mean 700-mb. charts for the periods indicated. At 60° N. the low wave numbers dominated much more strongly than at 40° N. On the other hand, amplitudes at 40° N. were much more evenly distributed over a fairly wide spectrum, with some tendency for maxima to appear at the very long wave end and again in the wave number band 5 through 7.

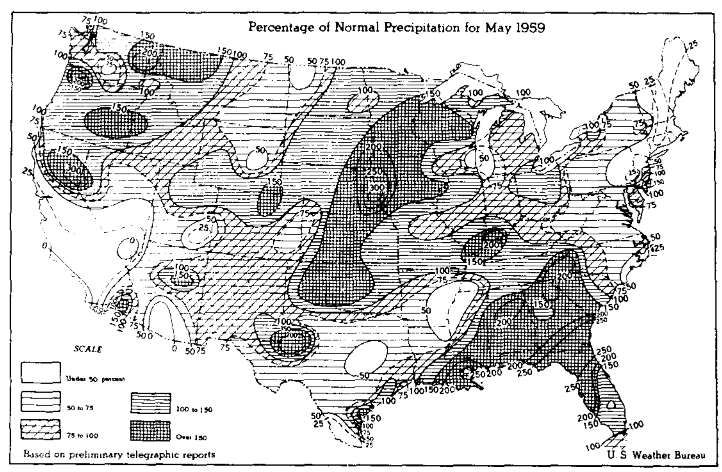


Figure 10.—Percentage of normal precipitation for May 1959. Precipitation was heavy over much of the Nation. Note the continued dryness in the Southwest and near the border of Montana and Wyoming with the Dakotas. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLVI, No. 23, 1959.)

7. PRECIPITATION

A large portion of the United States enjoyed adequate rainfall during May (fig. 10). Heaviest amounts fell over the Central Plains in advance of the mean trough position for the month (fig. 1), in the Northwest, and also in the Southeast. The heavy precipitation in the Southeast oc-

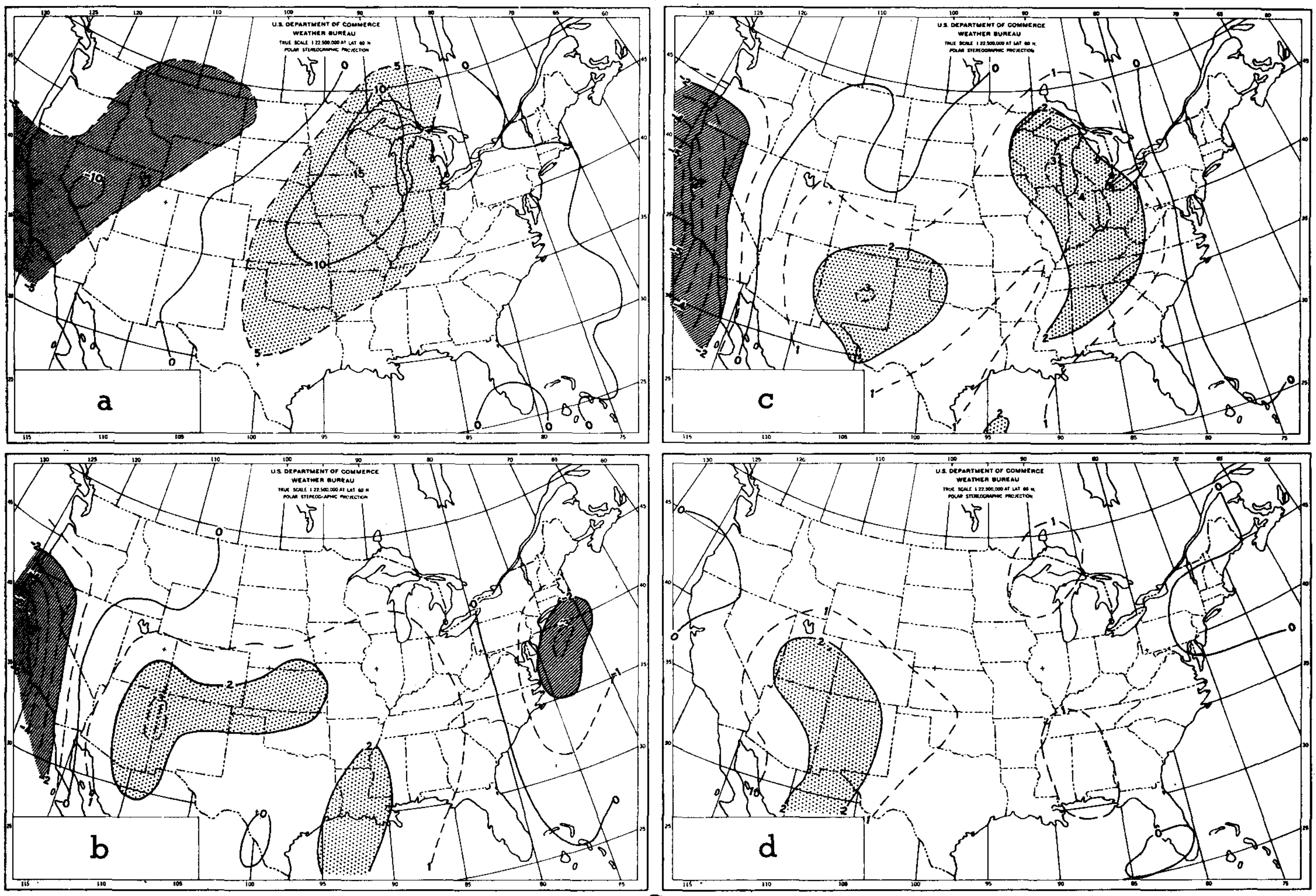


FIGURE 11.—Estimate of 30-day mean vertical motion for May 1959 in units of mm./sec., with positive values representing upward motion, obtained by: (a) advecting the mean 850–500-mb. thickness with the mean 500-mb. flow, (b) averaging 60 twice-daily values at 600 mb. computed from initial data by the JNWP baroclinic model, (c) applying the JNWP baroclinic model to the observed mean monthly 500-mb. contours and 850–500-mb. thickness data, (d) applying an equivalent barotropic model to the mean 500-mb. contours for the month. Only positive values of vertical motion were included.

curred during the latter half month, partly in connection with frequent locally heavy showers and thunderstorms, and also with a large contribution from tropical storm Arlene, particularly along the coastal section of Louisiana. Total rainfall at Rome, Ga., for example, reached 9.54 inches to set a new record since 1856.

The continued dry weather in the Southwest aggravated the existing drought situation in that area. Tucson, Ariz., experienced its first rainless May since 1949. The 0.32 in. recorded from January 1 to May 31 made this the driest comparable period since records began in 1868. Also, Oakland and Sacramento, Calif., with only traces, reported this month to be among the driest of record. Since January 1 El Paso, Texas, experienced only 0.73 in. (43 percent of normal) while Wichita Falls, Texas, reported this May to be the 10th consecutive month with subnormal precipitation.

New England and the Central Atlantic States were also relatively dry under the influence of anticyclonic flow and offshore winds. Hartford, Conn., and Scranton, Pa., for example, reported the driest May of record with monthly totals of only 0.73 and 0.77 in. respectively.

8. SPECIFICATION OF PRECIPITATION BY VERTICAL MOTION

The advent of the electronic computing machine has made possible routine computation of vertical motion in the middle troposphere. Several authors have recently discussed the relationship between this parameter and observed rainfall. Sanders [6], for example, investigated the occurrence of cloudiness and precipitation at certain cities in the United States and discussed their relationship to concurrent values of the dynamical, orographic, and frictional contributions to the vertical motion.

In the following experiment, several estimates of vertical motion were computed (fig. 11) and compared to the observed rainfall anomaly pattern (fig. 10). Since production of precipitation is a discontinuous and complex process dependent upon a number of parameters, use of this single variable can hardly be expected to account for the whole pattern.

The first of these charts (fig. 11a) depicts the advection of the mean thickness field (850 to 500 mb.) by the mean 500-mb. flow for the month. By assuming the thickness field to be stationary, which is a reasonable assumption on the monthly mean basis, the result can be interpreted in terms of upward motion. Comparison with the observed rainfall distribution (fig. 10) reveals a reasonable similarity between the two patterns. The relatively wet area in the central portion of the country appears to be fairly well delineated from the drier northeastern states by the line of neutral advection. In the Southeast, however, the advective pattern, though positive, does not support as much rainfall as occurred, particularly in eastern Georgia. In the mountainous areas of the West where orographic effects are likely to dominate, one is not surprised to find a poor relationship. In this region, however, although precipitation was greater than normal for the month, it totalled only one to two inches in absolute amount.*

The second chart (fig. 11b) was obtained by averaging the twice daily values of observed vertical motion at 600 mb. as computed from the two-level baroclinic model currently used by the Joint Numerical Weather Prediction Unit (JNWP). Also in this case, the resultant pattern bore a close correspondence to the observed rainfall pattern. The band of heavy precipitation extending from western Texas to the Great Lakes was associated with average upward motion as were the heavy rains in the Southeast. On the other hand, average descent in the Northeast and extreme Southwest was apparently quite effective in keeping those regions dry. As in the previous case, the correspondence was poor over the Northwest.

Figure 11c shows the vertical velocity obtained by using the monthly mean height at 500 mb. and thickness from 850 to 500 mb. as input data to the JNWP baroclinic model and running for one iteration. Thus this chart is closely akin to the previous one and the two would be the same if relationships between circulation and vertical motion were linear. The two charts are indeed quite similar, and most of the comments of the preceding paragraph apply in this instance also. The area of largest discrepancy over the United States lay over the States bordering Lake Michigan, where values computed in this manner were larger by 2 or 3 mm./sec. It is of interest that in both cases mean troughs were associated with rising motion in advance and sinking motion behind the trough line.

Figure 11d has been included to test the extent to which a simple model can capture the overall aspects of the monthly precipitation field, given the flow pattern. In this case the barotropic model described by Namias and collaborators [3] was applied to the mean 500-mb. flow except that the basic current was omitted (see appendix for method of computation of vertical motion). The model was designed to include positive vertical velocity only, on the assumption that precipitation might be better related to total upward motion than to the arithmetic average. Figure 11d was the result after one time step. Though the pattern was ill defined because the values were small, it bore a distinct resemblance to figure 11b, with cells of maximum positive vertical motion in the Southwest, the central Gulf States, and western Great Lakes Region. Each of these cells covered a region of considerable precipitation, though the area of very heavy rainfall along the Nebraska-Iowa border was not well indicated. Since the chart series, figure 11, constitutes but a single case, little in the way of conclusions can be drawn. However, they do suggest that continued research aimed at relating mean precipitation to a vertical motion parameter might be fruitful.

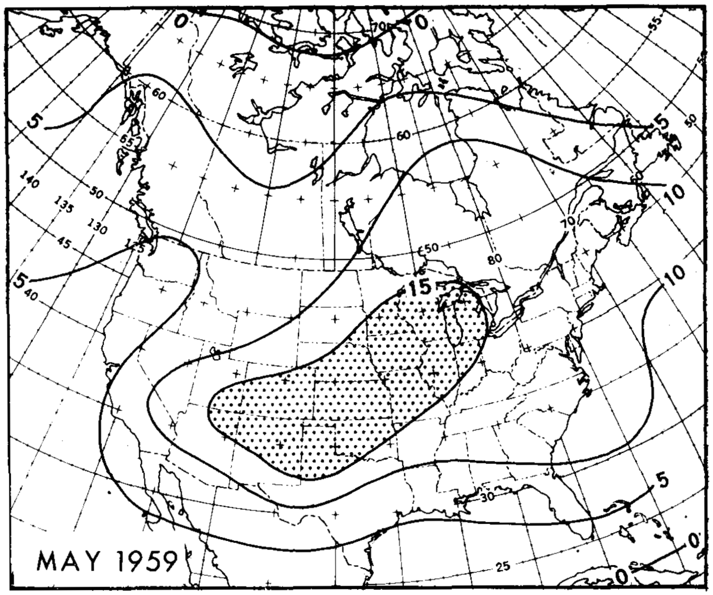


FIGURE 12.—Number of days in May 1959 with fronts of any type within unit squares (with sides approximately 500 miles). All frontal positions are taken from *Daily Weather Map*, 1300 EST. Areas with 15 days or more with fronts are stippled. Active fronts were frequent over the central portion of the country.

In general the charts (fig. 11) define an axis of maximum ascending motion extending roughly from western Texas to the Great Lakes. It is interesting that this agrees remarkably well with the position of the most frequent frontal activity during the month (fig. 12).

APPENDIX

The vertical motion w was estimated from the following equations derived by P. F. Clapp (personal communication).

The equivalent barotropic atmosphere is characterized by invariant wind direction with height so that if $\mathbf{V}_1$ is

*For total precipitation in inches see *Weekly Weather and Crop Bulletin*, vol. XLVI, No. 22, June 1, 1959.

the wind at one level, then the wind at a different level is $\mathbf{V}_2 = A\mathbf{V}_1$, where A is a function of height. Thus, if the subscript 1 is taken to refer to 500 mb. and the subscript 2 to 750 mb. and we assume conditions at 500 mb. to be nondivergent, the simplified vorticity equation at 500 and 750 mb. can then be written:

$$\frac{\partial \zeta_1}{\partial t} + \mathbf{V}_1 \cdot \nabla \zeta_1 + \mathbf{V}_1 \cdot \nabla f = 0 \tag{1}$$

$$\frac{\partial \zeta_2}{\partial t} + \mathbf{V}_2 \cdot \nabla \zeta_2 + \mathbf{V}_2 \cdot \nabla f - f\left(\frac{\partial \omega}{\partial p}\right)_2 = 0 \tag{2}$$

where the symbols have their usual meaning and ω_2 is the vertical velocity in terms of pressure coordinates. Combining (1) and (2) and noting that $\zeta_2 = A\zeta_1$, we obtain

$$\left(\frac{\partial \omega}{\partial p}\right)_2 = \frac{1}{f} A(A-1) \mathbf{V}_1 \cdot \nabla \zeta_1 = \frac{K}{f} \mathbf{V}_1 \cdot \nabla \zeta_1 \tag{3}$$

where K is a constant.

If we approximate $\left(\frac{\partial \omega}{\partial p}\right)_2$ by $\frac{\omega_3 - \omega_1}{p_1}$ and assume that ω at 1000 mb. (denoted by ω_3) is zero, then

$$\omega_1 = -\frac{p_1}{f} K \mathbf{V}_1 \cdot \nabla \zeta_1 \tag{4}$$

From the hydrostatic equation

$$\omega_1 = \left(\frac{dp}{dt}\right)_1 = -\rho_1 g w_1 \tag{5}$$

Thus w_1 can be estimated from (4) and (5) subject to the shortcomings of the equivalent barotropic model and the assumptions made above. In figure 11d it has been scaled in units of millimeters per second.

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